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Technical Memorandum

No. K-24/64

ANALYSIS OF THE PENETRATION OF ELECTRONIC COMPONENTS BY STEEL FRAGMENTS (U)

Gerald Hertweck
Dean R. Snyder

Computation and Analysis Laboratory

U. S. Naval Weapons Laboratory
Dahlgren, Virginia

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TECHNICAL MEMORANDUM

July 1964

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Approved by:

RALPH A. NIEMANN, Director
Computation and Analysis Laboratory

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ABSTRACT

This memorandum describes a technique for determining the materials, and their thicknesses, which possess fragment perforation characteristics most similar to certain electronic circuitry components, as established by test firings.

FOREWORD

The Tactical Weapons Analysis Branch, Computation and Analysis Laboratory, was requested by the Warhead and Terminal Ballistics Laboratory, Project Assistance Request RMMO-42-003/210-1/F008-08-06 of 12 August 1963, to provide a technique for determining materials "equivalent" to electronic circuitry components, in the sense that they possess similar fragment perforation characteristics. A method for solution of the problem was derived from the Project THOR analyses, and formulated as a computer program for an IBM 7030 computer by Mr. W. J. Graves, Head, Ballistic Sciences Branch.

INTRODUCTION

The requirements of the problem are to determine the materials that can best be used to simulate electronic circuitry components in computer-type studies of the vulnerability of electronic equipment to fragmenting warheads. The purpose in adopting this procedure is that if an "equivalence" relationship can be established with sufficient accuracy, the amount of penetration test data required for electronic items would be minimized, since a great deal of such data are readily available for various metallic and non-metallic materials from the Project THOR studies, references 1 and 2.

A method is described in this memorandum for determining the "equivalent" materials on the basis of the minimum error between the observed residual velocities of fragments perforating the electronic item and computed residual velocities for identical fragments perforating various metallic and non-metallic materials of some specified thickness. A computer program developed for this purpose is discussed in Appendix A. The results from using this program with data from a series of test firings of pre-formed steel fragments against selected electronic items are given in Table 3. Also, graphs showing the relationships among the fragment test data, "equivalent" materials, and the electronic items are presented in Figures 1 through 4.

EQUIVALENT MATERIALS AND THICKNESSES

The first phase of the analysis was to determine the materials and their thicknesses that are "equivalent" to electronic components, in the sense that they possess similar fragment perforation characteristics. The material type and thickness for a given electronic component and fragment data are selected on the basis of the minimum value of the error between the observed and calculated values of residual velocity for all materials considered.

Fragment perforation tests were conducted with four different fragment weights fired, with various initial velocities, into a capacitor, condenser, and two types of vacuum tubes. The fragment characteristics and velocities are summarized in Table 2. The characteristics of the materials which were compared to the fragment perforation data for the electronic components are defined by a set of constants derived in references 1 and 2, and are given in Table 1. These constants are defined in Appendix A. Using these data and the program described in Appendix A, the "equivalent" materials, material thicknesses, and an estimate of the residual velocity errors, shown in Table 3 were computed.

RELATIONSHIPS AMONG FRAGMENT DATA, EQUIVALENT MATERIALS, AND ELECTRONIC COMPONENTS

The second phase was to show the relationships among the fragment data and the materials and thicknesses "equivalent" to the electronic components tested.

Using the fragment data in Tables 1 and 2 and the "equivalent" material constants and thickness from Table 3, estimates of residual fragment velocity were computed, using the procedures described in reference 3, for a range of initial fragment velocities of 500-6000 feet/second and for the four fragment weights considered. The results of these computations are presented in graphical form in Figures 1-4.

REFERENCES

1. The Resistance of Various Metallic Materials to Perforation by Steel Fragments; Empirical Relationships for Fragment Residual Velocity and Residual Weight (U), Project THOR Technical Report No. 47, Ballistic Analysis Laboratory, Institute for Cooperative Research, The Johns Hopkins University, Baltimore, Maryland. April 1961. CONFIDENTIAL.

2. The Resistance of Various Non-Metallic Materials to Perforation by Steel Fragments; Empirical Relationships for Fragment Residual Velocity and Residual Weight (U), Project THOR Technical Report No. 51, Ballistics Analysis Laboratory, Institute for Cooperative Research, The Johns Hopkins University, Baltimore, Maryland. April 1963. CONFIDENTIAL.

3. Hertweck, G. and Cardwell, R., Programs for Fragment Penetration Analysis, U. S. Naval Weapons Laboratory Technical Memorandum No. K-100/63, U. S. Naval Weapons Laboratory, Dahlgren, Virginia. December 1963. CONFIDENTIAL

TABLE 1

MATERIAL CONSTANTS

MATERIAL	C	α	β	λ
UNBONDED NYLON	5.816	0.835	-0.654	-0.162
BONDED NYLON	4.672	1.144	-0.968	0.392
LEXON	2.908	0.720	-0.657	0.603
PLEXIGLAS (CAST)	5.243	1.044	-1.035	0.242
PLEXIGLAS (STRETCHED)	3.605	1.112	-0.903	0.686
DORON	7.600	1.021	-1.014	-0.362
BULLET-PROOF GLASS	3.743	0.705	-0.723	0.465
MAGNESIUM	6.904	1.092	-1.170	-0.087
ALUMINUM ALLOY 2024T-3	7.047	1.029	-1.072	-0.139
TITANIUM ALLOY	6.292	1.103	-1.095	0.167
CAST IRON	4.840	1.042	-1.051	0.523
FACE-HARDENED STEEL	4.356	0.674	-0.791	0.434
MILD HOMOGENEOUS STEEL	6.399	0.889	-0.945	0.019
HARD HOMOGENEOUS STEEL	6.475	0.889	-0.945	0.019
COPPER	2.785	0.678	-0.730	0.802
LEAD	1.999	0.499	-0.502	0.818
TUBALLOY	2.537	0.583	-0.603	0.828

FRAGMENT PERFORATION DATA

Striking Mass (Grains)	Impact Area $(Inches)^2$	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
METAL CLAD CAPACITOR			
5.8	0.03008	788.	0.
5.8	0.03008	1008.	0.
5.8	0.03008	1486.	0.
5.8	0.03008	1596.	0.
5.8	0.03008	1629.	0.
5.8	0.03008	1674.	521.
5.8	0.03008	1798.	320.
5.8	0.03008	1846.	664.
5.8	0.03008	1914.	473.
5.8	0.03008	1919.	465.
5.8	0.03008	1932.	910.
5.8	0.03008	2101.	860.
5.8	0.03008	2444.	867.
5.8	0.03008	2556.	875.
5.8	0.03008	2557.	1053.
5.8	0.03008	2656.	794.
5.8	0.03008	2782.	1498.
5.8	0.03008	2839.	1342.
5.8	0.03008	2870.	1544.
5.8	0.03008	2899.	587.
5.8	0.03008	3746.	1989.
5.8	0.03008	3750.	1952.
5.8	0.03008	3758.	1566.
5.8	0.03008	3857.	1477.
5.8	0.03008	3953.	1814.
6AS7G VACUUM TUBE			
5.8	0.03008	1543.	582.
5.8	0.03008	1639.	230.
5.8	0.03008	1765.	0.
5.8	0.03008	2284.	709.
5.8	0.03008	2368.	482.
5.8	0.03008	2458.	1592.
5.8	0.03008	2545.	1978.
5.8	0.03008	2571.	429.
5.8	0.03008	2697.	1592.
5.8	0.03008	2818.	2191.
5.8	0.03008	2830.	1431.
5.8	0.03008	2945.	1355.
5.8	0.03008	3043.	1592.
5.8	0.03008	3047.	1592.
5.8	0.03008	3075.	1661.
5.8	0.03008	3152.	2014.
5.8	0.03008	3177.	1530.
5.8	0.03008	3299.	1819.
5.8	0.03008	3436.	2403.
5.8	0.03008	4249.	2352.

Table 2

FRAGMENT PERFORATION DATA

6AU6 VACUUM TUBE

Striking Mass (Grains)	Impact Area (Inches)^2	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
5.8	0.03008	1229.	517.
5.8	0.03008	1339.	595.
5.8	0.03008	1351.	548.
5.8	0.03008	1354.	730.
5.8	0.03008	1363.	647.
5.8	0.03008	1371.	517.
5.8	0.03008	1422.	730.
5.8	0.03008	1432.	686.
5.8	0.03008	1466.	414.
5.8	0.03008	1473.	744.
5.8	0.03008	1489.	675.
5.8	0.03008	1510.	748.
5.8	0.03008	1587.	784.
5.8	0.03008	1593.	815.
5.8	0.03008	1595.	801.
5.8	0.03008	1607.	1053.
5.8	0.03008	1694.	806.
5.8	0.03008	1706.	870.
5.8	0.03008	1826.	555.
5.8	0.03008	1906.	1028.
5.8	0.03008	1966.	1019.
5.8	0.03008	1970.	892.
5.8	0.03008	2063.	990.
5.8	0.03008	2064.	1153.
5.8	0.03008	2074.	1107.
5.8	0.03008	2235.	1271.
5.8	0.03008	2237.	1218.
5.8	0.03008	2329.	1182.
5.8	0.03008	2386.	1245.
5.8	0.03008	2814.	1606.
5.8	0.03008	2820.	1564.
5.8	0.03008	2841.	1564.
5.8	0.03008	2879.	1513.
5.8	0.03008	2977.	1962.
5.8	0.03008	2990.	1675.
5.8	0.03008	3008.	2157.
5.8	0.03008	3128.	1751.
5.8	0.03008	4145.	2229.
5.8	0.03008	4161.	2656.
5.8	0.03008	4242.	2274.

Table 2 (Continued)

FRAGMENT PERFORATION DATA

Striking Mass (Grains)	Impact Area (Inches)^2	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
MICA CONDENSER			
17.0	0.03801	913.	360.
17.0	0.03801	994.	513.
17.0	0.03801	1027.	439.
17.0	0.03801	1075.	556.
17.0	0.03801	1293.	1025.
17.0	0.03801	1426.	863.
17.0	0.03801	1530.	1189.
17.0	0.03801	1553.	970.
17.0	0.03801	1559.	854.
17.0	0.03801	1703.	972.
17.0	0.03801	2011.	1384.
17.0	0.03801	2012.	1521.
17.0	0.03801	2067.	1367.
17.0	0.03801	2089.	1473.
17.0	0.03801	2168.	1559.
17.0	0.03801	2958.	2123.
17.0	0.03801	2959.	2418.
17.0	0.03801	2962.	2475.
17.0	0.03801	3050.	2328.
17.0	0.03801	3093.	2858.
METAL CLAD CAPACITOR			
17.0	0.03801	1428.	574.
17.0	0.03801	1456.	529.
17.0	0.03801	1481.	743.
17.0	0.03801	1541.	738.
17.0	0.03801	1680.	827.
17.0	0.03801	2036.	1106.
17.0	0.03801	2061.	1303.
17.0	0.03801	2093.	1486.
17.0	0.03801	2095.	1164.
17.0	0.03801	2123.	1335.
17.0	0.03801	2906.	1843.
17.0	0.03801	2908.	2336.
17.0	0.03801	2928.	2189.
17.0	0.03801	2946.	2284.
17.0	0.03801	2950.	2020.
17.0	0.03801	3801.	2235.
17.0	0.03801	3897.	2336.
17.0	0.03801	3915.	2565.
17.0	0.03801	3963.	2446.
17.0	0.03801	3968.	2630.
17.0	0.03801	3997.	2189.
17.0	0.03801	3997.	1957.
17.0	0.03801	4037.	2144.
17.0	0.03801	4040.	1957.
17.0	0.03801	4052.	2102.

Table 2 (Continued)

FRAGMENT PERFORATION DATA

Striking Mass (Grains)	Impact Area (Inches)^2	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
6AS7G VACUUM TUBE			
17.0	0.03801	1007.	143.
17.0	0.03801	1218.	694.
17.0	0.03801	1267.	761.
17.0	0.03801	1361.	511.
17.0	0.03801	2009.	912.
17.0	0.03801	2012.	1217.
17.0	0.03801	2042.	1230.
17.0	0.03801	2907.	1552.
17.0	0.03801	2965.	1952.
17.0	0.03801	2991.	1700.
17.0	0.03801	3904.	3026.
17.0	0.03801	3907.	2109.
17.0	0.03801	3920.	2641.
17.0	0.03801	3942.	2576.
17.0	0.03801	3955.	2245.
6AU6 VACUUM TUBE			
17.0	0.03801	854.	378.
17.0	0.03801	1045.	481.
17.0	0.03801	1090.	562.
17.0	0.03801	1124.	682.
17.0	0.03801	1308.	839.
17.0	0.03801	1402.	895.
17.0	0.03801	1520.	940.
17.0	0.03801	1522.	959.
17.0	0.03801	1556.	1027.
17.0	0.03801	1668.	1050.
17.0	0.03801	1694.	222.
17.0	0.03801	1989.	1356.
17.0	0.03801	2053.	1367.
17.0	0.03801	2079.	1356.
17.0	0.03801	2137.	1452.
17.0	0.03801	2146.	1485.
17.0	0.03801	2874.	2328.
17.0	0.03801	2932.	2244.
17.0	0.03801	3064.	2214.
17.0	0.03801	3114.	2230.
17.0	0.03801	3148.	2168.

Table 2 (Continued)

FRAGMENT PERFORATION DATA

Striking Mass (Grains)	Impact Area (Inches)^2	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
METAL CLAD CAPACITOR			
44.0	0.07069	947.	263.
44.0	0.07069	958.	286.
44.0	0.07069	965.	428.
44.0	0.07069	971.	196.
44.0	0.07069	1030.	259.
44.0	0.07069	1618.	1023.
44.0	0.07069	1632.	968.
44.0	0.07069	1638.	1004.
44.0	0.07069	1651.	950.
44.0	0.07069	1671.	1004.
44.0	0.07069	1982.	1482.
44.0	0.07069	1987.	1367.
44.0	0.07069	2001.	1315.
44.0	0.07069	2032.	1332.
44.0	0.07069	2059.	1404.
44.0	0.07069	2934.	2311.
44.0	0.07069	3001.	2311.
44.0	0.07069	3003.	2364.
44.0	0.07069	3005.	2260.
44.0	0.07069	3021.	2260.
MICA CONDENSER			
44.0	0.07069	961.	934.
44.0	0.07069	1028.	927.
44.0	0.07069	1624.	1315.
44.0	0.07069	1646.	1404.
44.0	0.07069	1659.	1504.
44.0	0.07069	1684.	1315.
44.0	0.07069	1699.	1549.
44.0	0.07069	1948.	1441.
44.0	0.07069	1968.	1462.
44.0	0.07069	1994.	1597.
44.0	0.07069	2017.	1549.
44.0	0.07069	2081.	1789.
44.0	0.07069	2925.	2421.
44.0	0.07069	2982.	2746.
44.0	0.07069	2983.	2421.
44.0	0.07069	3000.	2479.
44.0	0.07069	3046.	2541.

Table 2 (Continued)

FRAGMENT PERFORATION DATA

Striking Mass (Grains)	Impact Area (Inches)^2	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
6AS7G VACUUM TUBE			
44.0	0.07069	699.	389.
44.0	0.07069	762.	375.
44.0	0.07069	899.	444.
44.0	0.07069	956.	556.
44.0	0.07069	965.	215.
44.0	0.07069	999.	482.
44.0	0.07069	1627.	1086.
44.0	0.07069	1661.	1283.
44.0	0.07069	1662.	1143.
44.0	0.07069	1663.	1013.
44.0	0.07069	1675.	994.
44.0	0.07069	2053.	1572.
44.0	0.07069	2057.	1549.
44.0	0.07069	2083.	1525.
44.0	0.07069	2103.	1549.
44.0	0.07069	2131.	1385.
44.0	0.07069	2922.	2212.
44.0	0.07069	2998.	2312.
44.0	0.07069	3001.	2312.
44.0	0.07069	3034.	2312.
44.0	0.07069	3106.	2121.
6AU6 VACUUM TUBE			
44.0	0.07069	610.	258.
44.0	0.07069	614.	319.
44.0	0.07069	623.	259.
44.0	0.07069	665.	307.
44.0	0.07069	684.	422.
44.0	0.07069	917.	597.
44.0	0.07069	965.	656.
44.0	0.07069	966.	578.
44.0	0.07069	970.	630.
44.0	0.07069	1048.	840.
44.0	0.07069	1622.	1157.
44.0	0.07069	1655.	1239.
44.0	0.07069	1659.	1169.
44.0	0.07069	1662.	1208.
44.0	0.07069	1693.	1268.
44.0	0.07069	1928.	1546.
44.0	0.07069	1967.	1482.
44.0	0.07069	1969.	1504.
44.0	0.07069	1985.	1504.
44.0	0.07069	1990.	1462.
44.0	0.07069	2959.	2365.
44.0	0.07069	2968.	2213.
44.0	0.07069	2992.	2420.
44.0	0.07069	3000.	2479.
44.0	0.07069	3050.	2479.

Table 2 (Continued)

FRAGMENT PERFORATION DATA

Striking Mass (Grains)	Impact Area (Inches)^2	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
MICA CONDENSER			
208.0	0.19640	573.	511.
208.0	0.19640	591.	571.
208.0	0.19640	593.	479.
208.0	0.19640	613.	583.
208.0	0.19640	641.	511.
208.0	0.19640	878.	726.
208.0	0.19640	882.	760.
208.0	0.19640	967.	823.
208.0	0.19640	984.	831.
208.0	0.19640	1028.	949.
208.0	0.19640	1033.	919.
208.0	0.19640	1050.	932.
208.0	0.19640	1491.	1444.
208.0	0.19640	1527.	1361.
208.0	0.19640	1543.	1552.
208.0	0.19640	1581.	1412.
208.0	0.19640	1581.	1417.
208.0	0.19640	1966.	1756.
208.0	0.19640	1986.	1771.
208.0	0.19640	2006.	1756.
208.0	0.19640	2017.	1763.
208.0	0.19640	2842.	2689.
208.0	0.19640	2972.	2671.
208.0	0.19640	3066.	2689.
208.0	0.19640	3066.	2877.
208.0	0.19640	3115.	2764.

Table 2 (Continued)

FRAGMENT PERFORATION DATA

Striking Mass (Grains)	Impact Area $(\text{Inches})^2$	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
METAL CLAD CAPACITOR			
208.0	0.19640	662.	467.
208.0	0.19640	656.	591.
208.0	0.19640	924.	675.
208.0	0.19640	927.	631.
208.0	0.19640	938.	622.
208.0	0.19640	950.	716.
208.0	0.19640	957.	258.
208.0	0.19640	964.	652.
208.0	0.19640	974.	621.
208.0	0.19640	984.	757.
208.0	0.19640	1026.	729.
208.0	0.19640	1056.	814.
208.0	0.19640	1063.	816.
208.0	0.19640	1418.	1107.
208.0	0.19640	1438.	1060.
208.0	0.19640	1470.	994.
208.0	0.19640	1473.	1060.
208.0	0.19640	1474.	1205.
208.0	0.19640	1495.	1057.
208.0	0.19640	1513.	1234.
208.0	0.19640	1569.	1255.
208.0	0.19640	1572.	1255.
208.0	0.19640	1674.	1026.
208.0	0.19640	1903.	1550.
208.0	0.19640	1920.	1559.
208.0	0.19640	1921.	1574.
208.0	0.19640	1973.	1676.
208.0	0.19640	1983.	1625.
208.0	0.19640	1999.	1429.
208.0	0.19640	2053.	1416.
208.0	0.19640	2058.	1422.
208.0	0.19640	2174.	1528.
208.0	0.19640	2295.	1585.
208.0	0.19640	2929.	2463.
208.0	0.19640	2998.	2463.
208.0	0.19640	3071.	2543.
208.0	0.19640	3093.	2564.
208.0	0.19640	3153.	2608.
208.0	0.19640	1802.	1568.
208.0	0.19640	3154.	2653.
208.0	0.19640	3159.	2675.
208.0	0.19640	3162.	2653.
208.0	0.19640	3183.	2586.
208.0	0.19640	3196.	2635.

Table 2 (Continued)

FRAGMENT PERFORATION DATA

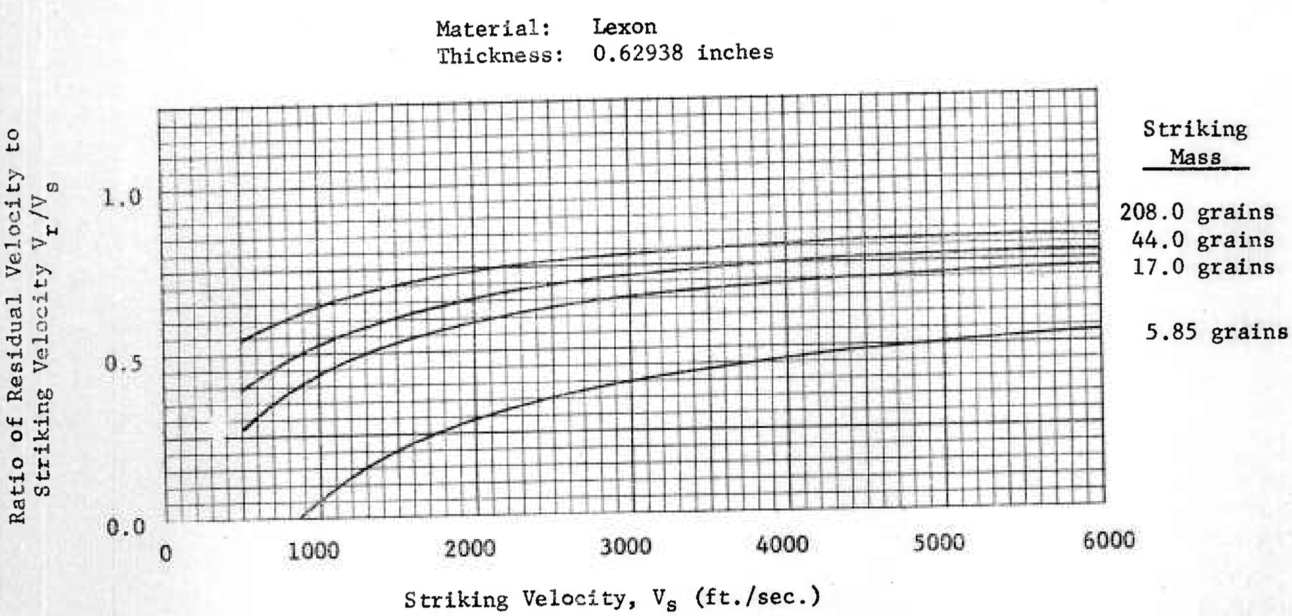
Striking Mass (Grains)	Impact Area $(Inches)^2$	Striking Velocity (ft/sec)	Residual Velocity (ft/sec)
6AS7G VACUUM TUBE			
208.0	0.19640	475.	297.
208.0	0.19640	561.	349.
208.0	0.19640	595.	396.
208.0	0.19640	596.	464.
208.0	0.19640	722.	434.
208.0	0.19640	947.	658.
208.0	0.19640	1002.	690.
208.0	0.19640	1028.	825.
208.0	0.19640	1054.	814.
208.0	0.19640	1070.	845.
208.0	0.19640	1526.	1278.
208.0	0.19640	1595.	1354.
208.0	0.19640	1678.	1454.
208.0	0.19640	1837.	1654.
208.0	0.19640	1927.	1628.
208.0	0.19640	1928.	1666.
208.0	0.19640	2145.	1758.
208.0	0.19640	2863.	2581.
208.0	0.19640	3165.	2754.
208.0	0.19640	3192.	2792.
208.0	0.19640	3248.	2797.
6AU6 VACUUM TUBE			
208.0	0.19640	499.	368.
208.0	0.19640	1341.	1156.
208.0	0.19640	1463.	1263.
208.0	0.19640	1478.	1363.
208.0	0.19640	1494.	1300.
208.0	0.19640	1497.	1311.
208.0	0.19640	1737.	1462.
208.0	0.19640	1838.	1602.
208.0	0.19640	1941.	1650.
208.0	0.19640	1962.	1650.
208.0	0.19640	2089.	1721.
208.0	0.19640	2773.	2387.
208.0	0.19640	2905.	2564.
208.0	0.19640	3137.	2608.
208.0	0.19640	3140.	2675.
208.0	0.19640	3147.	2723.

Table 2 (Continued)

Table 3

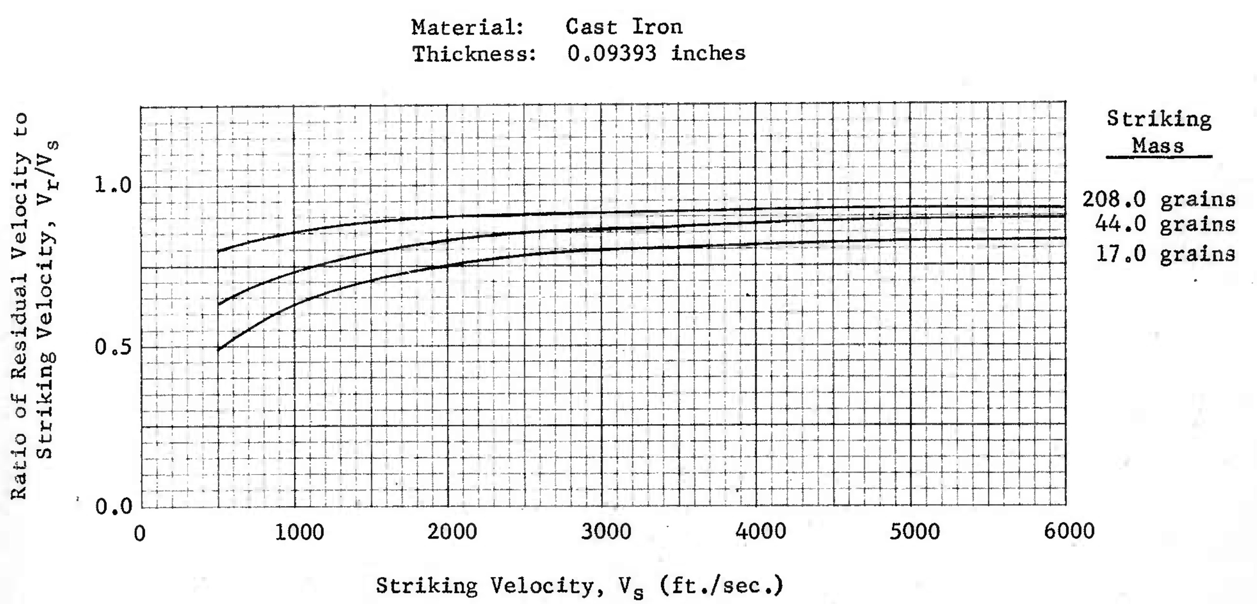
EQUIVALENT MATERIALS AND THICKNESSES

Electronic Component	Equivalent Material	Equivalent Thickness (in.)	Prediction Error (ft/sec)
Metal-clad Capacitor	Lexon	0.62938	239.4
Mica Condenser	Cast iron	0.09393	126.9
6AS7G Vacuum Tube	Lexon	0.50719	293.9
6AU6 Vacuum Tube	Lexon	0.38909	151.8



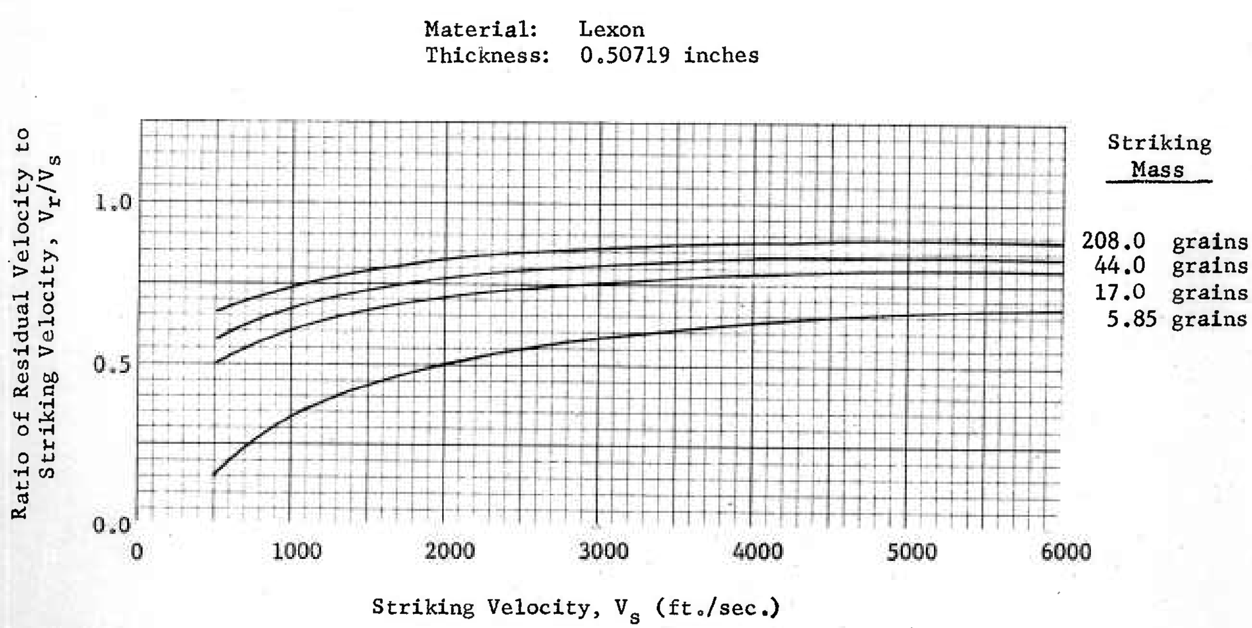
RATIO OF FRAGMENT RESIDUAL VELOCITY TO STRIKING VELOCITY VERSUS STRIKING VELOCITY FOR MATERIAL EQUIVALENT TO METAL CLAD CAPACITOR

Figure 1



RATIO OF FRAGMENT RESIDUAL VELOCITY TO STRIKING VELOCITY VERSUS STRIKING VELOCITY FOR MATERIAL EQUIVALENT TO MICA CONDENSER

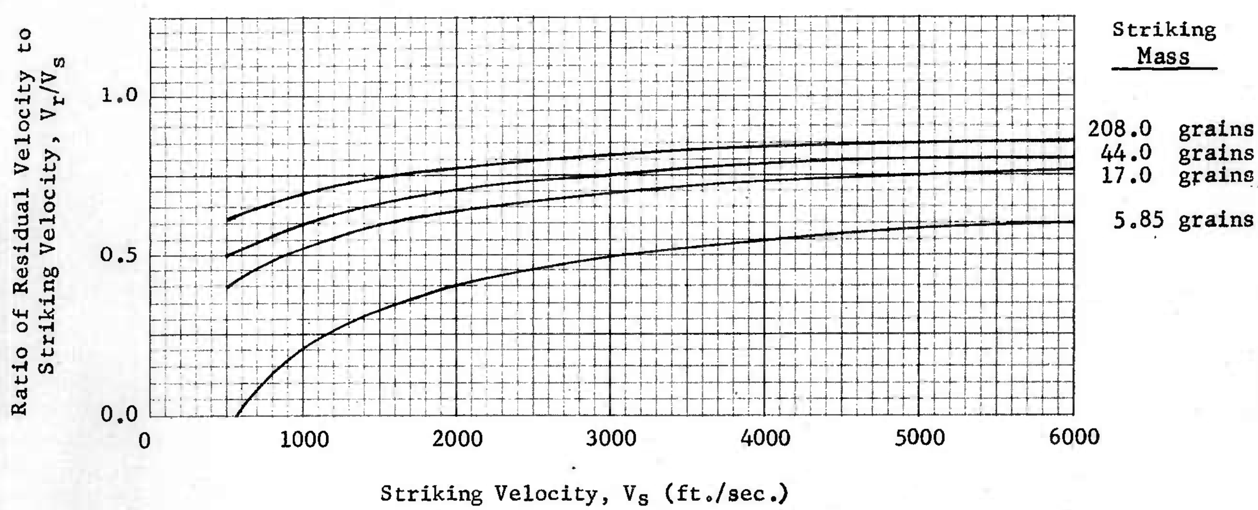
Figure 2



RATIO OF FRAGMENT RESIDUAL VELOCITY TO STRIKING VELOCITY VERSUS STRIKING VELOCITY FOR MATERIAL EQUIVALENT TO 6AS7G VACUUM TUBE

Figure 3

Material: Lexon
Thickness: 0.38909 inches



RATIO OF FRAGMENT RESIDUAL VELOCITY TO STRIKING VELOCITY VERSUS STRIKING VELOCITY FOR MATERIAL EQUIVALENT TO 6AU6 VACUUM TUBE

Figure 4

APPENDIX A

COMPUTER PROGRAM FOR SELECTION OF MATERIALS AND THICKNESSES POSSESSING PERFORATION CHARACTERISTICS SIMILAR TO ELECTRONIC COMPONENTS

A computer program has been developed to determine the materials and appropriate thicknesses which are "equivalent" to electronic components in the sense that they possess similar fragment perforation characteristics.

In references 1 and 2, an empirical equation relating residual velocity to important impact parameters for both metallic and non-metallic materials is given as:

$$V_r = V_s - 10^c \, (eA)^{\alpha} \, M_s^{\beta} \, (\sec \theta)^{\gamma} \, V_s^{\lambda}$$

where

V_r = residual velocity of fragment, feet/second

V_s = striking velocity of fragment, feet/second

e = material thickness, inches

A = average impact area of fragment, (inches)^2

M_s = initial weight of fragment, grains

θ = angle of fragment trajectory from normal to target, degrees

and c, α, β, γ, and λ are constants determined by fitting the equation to experimental perforation data by the method of least squares.

For materials described by the above material constants and for given fragment test data, a material thickness, e, can be calculated which minimizes the error function σ, where

$$\sigma = \left[\frac{\sum_{i=1}^{n} (V_{r_i} - V'_{r_i})^2}{n - 1} \right]^{\frac{1}{2}}$$

and,

V_{r_i} = observed residual velocity of each fragment

V'_{r_i} = computed residual velocity of each fragment

It can be shown by elementary calculus that σ is a minimum when

$\sum_{i=1}^{n} V'_{r_i} = \sum_{i=1}^{n} V_{r_i}$. Recalling that $V'_{r_i} = V_{s_i} - 10^C (eA)^{\alpha} M_s^{\beta} (\sec \theta)^{\gamma} V_{s_i}^{\lambda}$,

the following mathematical expression may be obtained for e,

$$e = \left[\frac{\sum_{i=1}^{n} (V_{s_i} - V_{r_i})}{10^C A^{\alpha} M^{\beta} \sum_{i=1}^{n} (V_{s_i})^{\lambda}} \right]^{1/\alpha}$$

The parameter, $(\sec \theta)^{\gamma}$, is eliminated from the equation since the fragment trajectory angle is zero under testing conditions.

The appropriate material and thickness, for a given electronic component and fragment data, are selected on the basis of the minimum calculated value of σ for all materials considered.

The procedure described above is outlined in detail in the flow diagram in Figure A-1. The input format and a listing of the FORTRAN IV program deck are provided in Figures A-2 and A-3. A sample output format is shown in Figure A-4.

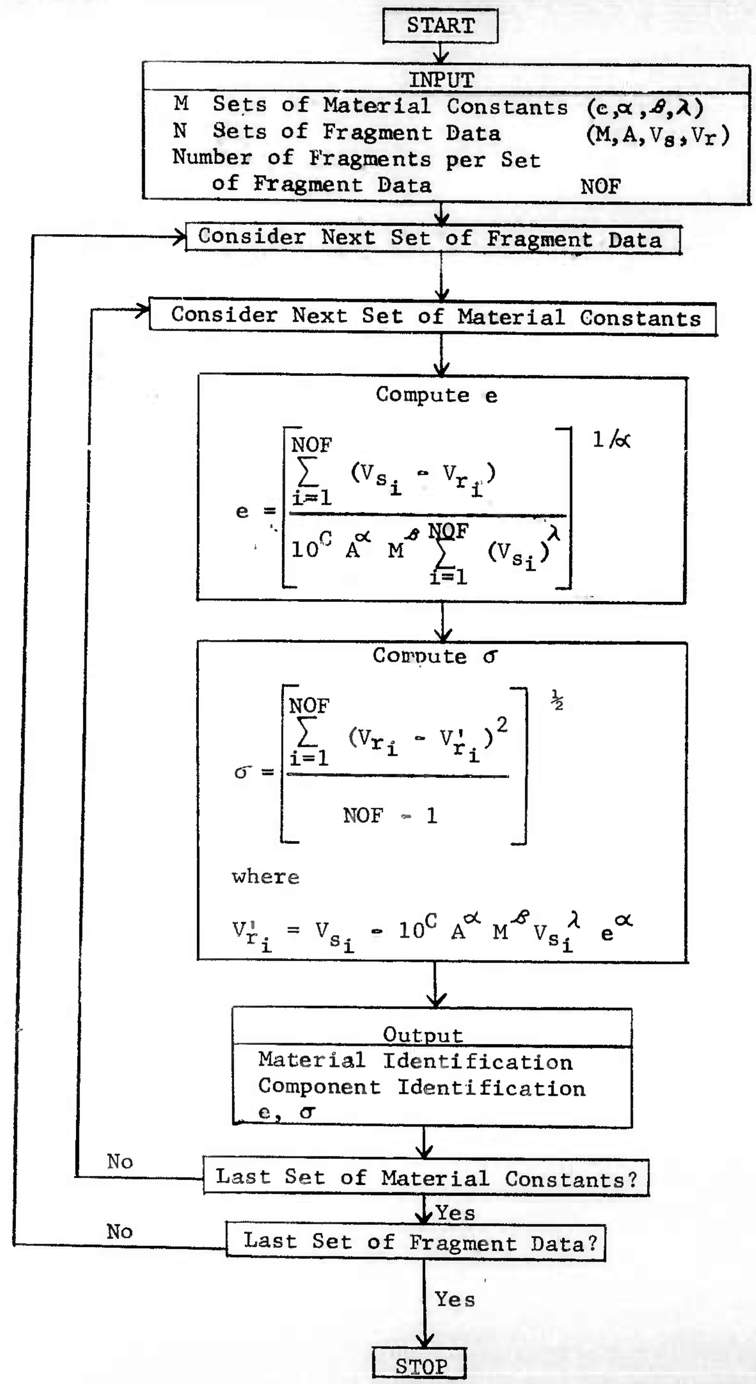


Figure A-1. Flow Diagram

INPUT FORMAT

Card Type 1	M	Number of sets of material constants.
	N	Number of sets of fragment data.
Card Type 2	Material Identification	Identifies material (may use 72 columns).
Card Type 3	$c, \alpha, \beta, \lambda$	Appropriate values of material constants.

Repeat Cards 2 and 3 until all materials are entered.

Card Type 4	Fragment Identification	Identifies set of fragment data.
	NOF	Number of fragments in set of data.
Card Type 5	M_s	Striking Mass (grains).
	A	Impact Area $(\text{inches})^2$.
	V_s	Striking Velocity (ft/sec).
	V_r	Residual Velocity (ft/sec).

One Card Type 5 is prepared for each fragment in set of data. Repeat Card Types 4 and 5 until all sets of fragment data are entered.

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DATA CARD LAYOUT

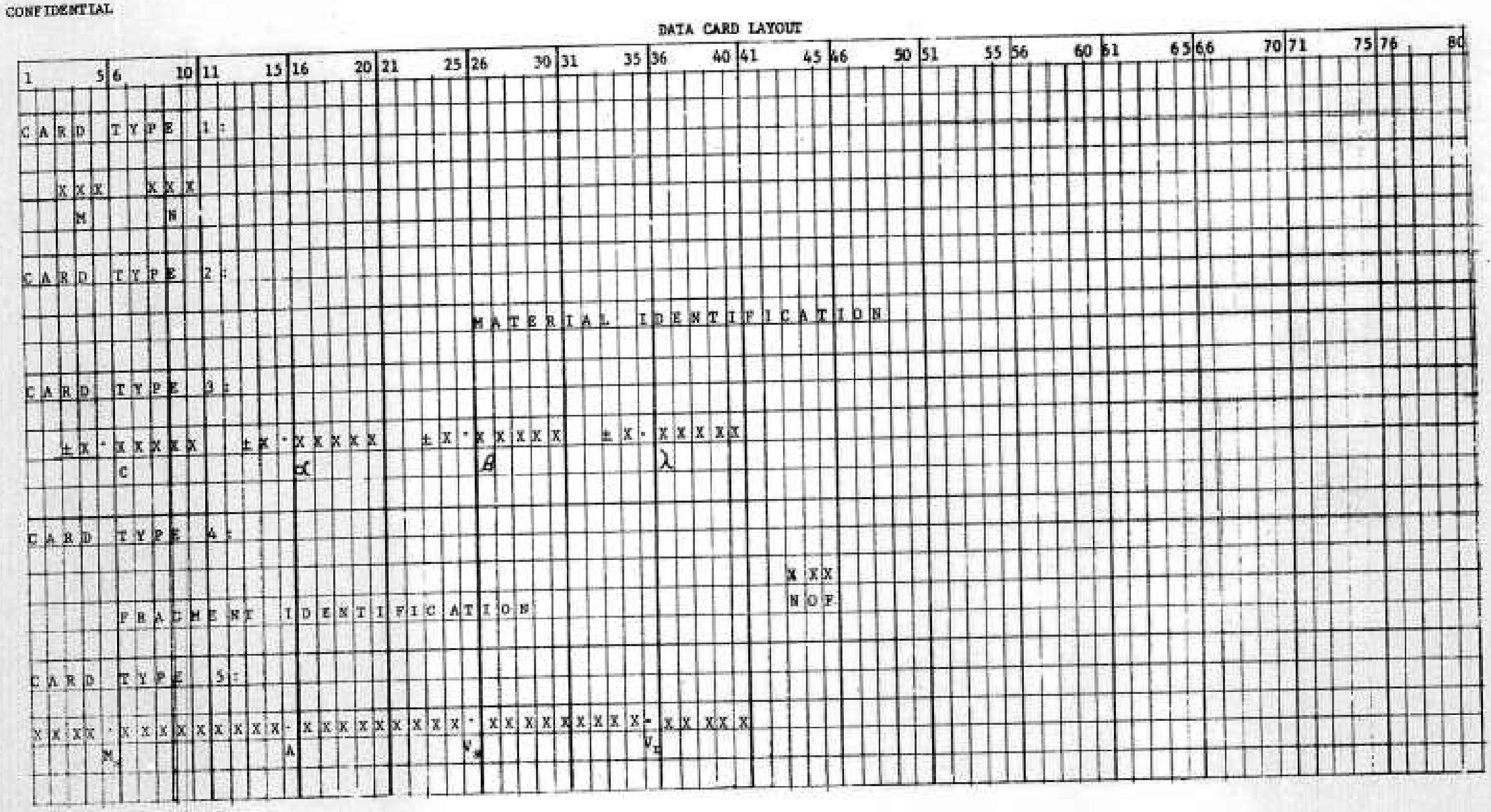

FIGURE A-2. INPUT FORMAT

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DATA CARD LAYOUT

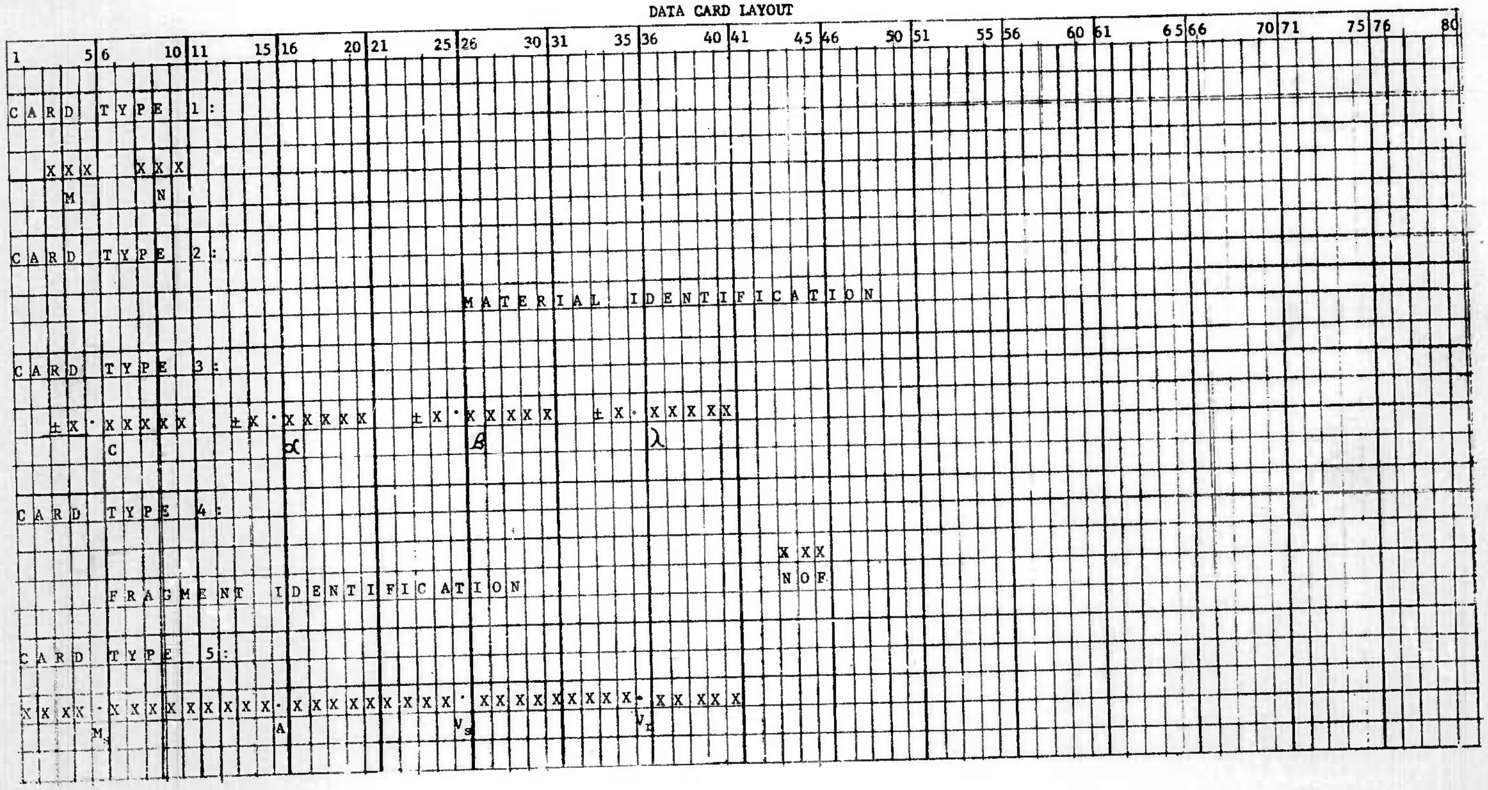

FIGURE A-2. INPUT FORMAT

```
100 FORMAT (12A6)
101 FØRMAT (4F10.5)
102 FØRMAT (9A5,I5)
103 FØRMAT (2I5)
    DIMENSIØN EM(500),A(500),VI(500),VR(500),MID(1200),DID(9),C(100),
   1ALPHA(100),BETA(100),ALAMDA(100)
104 FØRMAT (1HJ,12A6)
105 FØRMAT (1HJ,9A5)
106 FØRMAT (1HJ,2E17.10)
  5 READ 103,M,N
    DØ 1 I=1,M
    J=12*I
    K=J-11
    READ 100,(MID(L),L=K,J)
  1 READ 101,C(I),ALPHA(I),BETA(I),ALAMDA(I)
    DØ 4 IA=1,N
    READ 102,DID,NØF
    READ 101,(EM(I),A(I),VI(I),VR(I),I=1,NØF)
    DØ 4  J=1,M
    B1=0.
    B2=0.
    B4=(10.**C(J))
    DØ 2 I=1,NØF
    B1=VI(I)-VR(I)+B1
    B6=(A(I)**ALPHA(J))*(EM(I)**BETA(J))
    B7=VI(I)**ALAMDA(J)
  2 B2=B2+B4*B6*B7
    EALFA=B1/B2
    E=EALFA**(1./ALPHA(J))
    B3=0.
    B5=B4*EALFA
    DØ 3 I=1,NØF
    B6=VI(I)-B5*(A(I)**ALPHA(J))*(EM(I)**BETA(J))*(VI(I)**ALAMDA(J))-
   1VR(I)
  3 B3=B3+B6*B6
    B6=NØF-1
    S=SQRT(B3/B6)
    K=12*J
    L=K-11
    PRINT 104,(MID(I),I=L,K)
    PRINT 105,DID
  4 PRINT 106,E,S
    GØ TØ 5
    END
```

Figure A-3. Program Deck Listing.

```
BULLET-PRØØF GLASS

CØNDENSER

 0.9904226930E-01 0.1371180534E+03

MAGNESIUM

CØNDENSER

 0.1495236572E-00 0.1412786815E+03

ALUMINUM ALLØY  2024T-3

CØNDENSER

 0.8389952371E-01 0.1490570050E+03

TITANIUM ALLØY

CØNDENSER

 0.7852643271E-01 0.1310332128E+03

CAST IRØN

CØNDENSER

 0.9392946520E-01 0.1269118118E+03

FACE-HARDENED STEEL

CØNDENSER

 0.2002214531E-01 0.1272961626E+03

MILD HØMØGENEØUS STEEL

CØNDENSER

 0.3122708173E-01 0.1401695030E+03

HARD HOMØGENEØUS STEEL

CØNDENSER

 0.2564732564E-01 0.1401695030F+03

COPPER

CØNDENSER

 0.5115912822E-01 0.1423751516E+03
```

Figure A-4. Sample Output.